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There have been considerable changes in the VCSEL marketplace since *III-Vs Review* last visited the subject. Nevertheless, prospects are pretty good, with plenty of new life left yet. Improving processes are yielding devices with better performance. This promises to open up new applications not only for displays and instrumentation but also for higher-bandwidth, longer-reach metropolitan data communications networks, where so much expectation lies, as well as other as-yet untapped applications.

VCSEL applications diversify as technology matures

Vertical-cavity surface-emitting lasers (VCSELs) made their debut over 10 years ago. Since then, they have become a staple component for a wide range of applications, especially in networks. They have replaced edge-emitting lasers in applications for short-range fibre optics, notably Gigabit Ethernet and Fibre Channel. However, recent developments should ensure that other fields will become important in due course.

Due to tougher-than-expected technology challenges and the downturn in communications market sectors, the number of VCSEL companies in the industry has been depleted

At one time VCSELs were the most popular product for high-profile start-up companies. Since then, due to tougher-than-expected technology challenges and the downturn in communications market sectors that these start-ups were targeting, the number of VCSEL companies in the industry has been depleted. Attrition is inevitable in high-tech markets, but it has not been all gloom. The VCSEL has established a firm place in the market thanks to the good performance/cost combination of 850 nm wavelength devices. The next opportunity for VCSEL makers is to target the longer-wavelength networks sector, expanding out of the short-reach 850 nm market.

Even though Honeywell, the pioneer of commercial VCSELs, has moved into other areas, many companies are interested in the future path for VCSELs. Although some other companies have disappeared, new ones have sprung up.

For example, Switzerland's LITRAX GmbH introduced an 850 nm implant single-mode (SM) VCSEL and laser bundles for applications requiring a reflected signal. This typifies the technical advances that have been made behind the scenes. Though attention is shifting to the 1300 nm wavelength, these 850 nm implant single-mode VCSELs represent a new generation of VCSELs that is superior in reliability and performance to the oxide VCSELs currently on the market. In addition, on the commercial side, they provide cost and design advantages, including compact size, low threshold current (allowing for lower power consumption), and superior output power, with a tightly focused beam that enables the device to operate extremely accurately on many smooth surfaces.

Last September, Alight Technologies A/S acquired Infineon Technologies' interests in 1300 nm GaInNAs VCSEL platforms. Alight is targeting emerging telecom access markets, such as the fibre to the home (FTTH) and high-bit-rate datacom markets. Other well established companies have also been active. Earlier in the year, Panasonic revealed an 850 nm VCSEL capable of modulation at a data rate of 12.5 Gb/s at a low operating current of 8 mA. Target applications include lower-cost plastic optical fibre communications and spatial light transmission.

Communications success

The main province of the 850 nm VCSEL has to be in short-range optical storage area networks (SANs). The SAN segment has been a success story for VCSELs for quite a while now. Nonetheless, it is a tough, price-sensitive marketplace, so it is not surprising that vendors are looking for other avenues.

Due to the competitive SAN market, 850 nm VCSEL makers have been forced to accelerate the move to longer or shorter wavelengths to provide them with better margins. This has meant substantial technical investment. All the

time, other types of diode laser are being repositioned to satisfy the need for more bandwidth at a data rate of 10 Gb/s. Some are predicting that it might squeeze out VCSELs from the market. Nevertheless, others are more confident of a VCSEL revival developing as the device family diversifies. Even though connectivity over long-reach applications (at or above 10 km) is a challenge, it is an irresistible business opportunity.

From the materials perspective, longer-wavelength VCSELs mean that nitride- and antimonide-based III-Vs compounds are having to be considered. Each material has its advantages, depending on who is defending their corner. Moreover, the epitaxial growth know-how is going to be even more important than it was for the 850 nm wavelength, which in itself was deceptively complex. Some market observers are sceptical of the VCSEL's chances of success at longer wavelengths. While VCSELs emitting in the 1300 nm and 1550 nm wavelength ranges can be made more cheaply than most other types of diode laser in this category, these new material structures have yet to be proven. Supplier reliability data will be a highly important subject for some time yet.

VCSELs have to face the lower prices of Fabry–Perot (FP) and distributed feedback (DFB) lasers, which makes market entry for VCSEL products much more difficult; unless, of course, they can introduce genuinely superior technical characteristics into the bargain, such as wavelength stability, etc (see below).

In the extreme, some observers suggest that it may already be too late for longer-wavelength VCSELs to succeed in the market. In spite of this, several companies are launching products and remain optimistic. Overall, the view is cautiously bright.

Last year, Picolight Inc became the first to ship 1310 nm VCSEL transceivers in a 4 Gb/s triple-rate (1, 2 and 4 Gb/s) Small Form-Factor Pluggable (SFP) configuration. Thanks to extended reach capability and low power consumption, the transceivers satisfy a broad range of short-to-medium distance applications, including 4 Gb/s Fibre Channel (FC) at 10 km for SANs. Similarly to 850 nm VCSEL transceivers, 1310 nm VCSEL transceivers have the potential to dominate short-to-medium distance single-mode fibre applications, displacing existing edge-emitting laser transceivers in high-bandwidth and high-density optical systems.

At the time, Steve Hane, Picolight's president and CEO said, "We intend to leverage our 1310 nm VCSEL development efforts in multiple new markets and applications, including high-bandwidth and high-density optical platforms. Compared to competing technologies, our 4 Gb/s SFP 1310 nm VCSELs deliver lower power consumption, lower electromagnetic interference (EMI) and lower heat generation, resulting in increased performance and reliability over single-mode fibre for Fibre Channel systems customers."

Vidya Sharma, Picolight's vice president of marketing, adds: "Because of the high drive currents of edge-emitting lasers, module-level heat dissipation is becoming limiting for high-density, high-bandwidth systems. Next-generation high-density form factors will strongly favour exclusive use of VCSEL technology due to its low heat and low EMI-generation characteristics."

Another company that is closely observing this market is BeamExpress of Switzerland. This company began addressing the transceiver module market with 1550 nm VCSELs. But, due to the deteriorating market conditions, it had to shift into the LX4 transceiver market. (LX4 splits a 10 Gb/s Ethernet feed into four 3.125 Gb/s channels, and is one option for 10 Gb/s over short distances on older multimode fibre.) Also, former MOCVD systems specialist Emcore acquired the LX4 business of Molex. In addition, Emcore's continuing interest in lasers is confirmed by its recent acquisition of K2 Optronics, which was the first company to commercialize the concept of external-cavity lasers (ECLs) in industry-standard 14-pin butterfly packages. Representative of the business today, Emcore offers a range of cooled and uncooled products in the form of both chips and bare die, which includes 850 nm VCSELs and arrays as well as FP and DFB products. Blaze Networks was the first commercial venture to exploit wavelength division multiplexing (WDM) for short-wavelength and data communications applications. The company has a 10 Gb/s module (designed for optical connect applications under 300 m range, including Gigabit Ethernet and Fiber Channel) that is based on Emcore's VCSEL technology.

Charles Wang, Director of Module Development for Emcore's Fiber Optics Division, said: "We are seeing broad industry-wide expansion of 10 Gigabit Ethernet. As the breadth and depth of systems expand, Emcore continues to provide products which address the market's need for

These 850 nm implant single-mode VCSELs represent a new generation of VCSELs that is superior in reliability and performance to oxide VCSELs

innovative pluggable devices. Emcore's new CX4 units provide a robust, cost-effective solution which complements our other 10 Gb/s electrical and optical XENPAK and X2 options." Emcore has said that, though costs favour other lasers for 10 Gb/s long-reach applcations, it is looking at 1310 nm VCSEL devices.

Photodigm Inc of Richardson, TX, USA was one of the first companies to achieve a breakthrough in 1310 nm grating-outcoupled surface emitting (GSE) laser technology. This translates into devices with single-mode output powers of up to 6 mW. Basically, it combines the performance of a DFB laser with the advantages of a VCSEL. Until then, 1310 nm lasers were available only as edge-emitting lasers. While the industry has devoted huge resources towards the development of surface-emitting 1310 nm VCSELs, the results have generally been mixed. Photodigm's GSE laser uses a proven edge-emitting epitaxial material structure (AlInGaAs/InP) and relies on first- and second-order gratings for the DBR reflectors and the outcoupler.

Due to the competitive SAN market, 850 nm VCSEL makers have been forced to accelerate the move to longer or shorter wavelengths

Karlheinz Gulden of Avalon Photonics notes that "Since VCSELs became commercially available 10 years ago, the vast majority of devices were used in datacom applications. This situation is about to change. I would expect that 2006 is the first year in which more VCSELs are shipped into non-datacom applications than datacom applications (on an annual bases). Avalon is set to profit from this development. We have shifted our focus from communications to sensor applications and we are well positioned to participate in this dynamic development."

POF and FSO

Other key applications for VCSELs in communications networks include plastic optical fibre (POF) and free-space optics (FSO). Various companies are now pitching their technologies into these areas. For example, Declan O'Mahoney, CEO of Ireland's Firecomms, says, "We have been developing 650–680 nm VCSEL-based transceivers which enable visible light to run through large-core plastic fibre at modulations up to 3.2 Gb/s. The advantage is that POF is easier to install than copper at these data rates, so it has opened up a sizeable new market in lower-cost networking."

Figure 1. Firecomms' FC665nm VCSEL is the first commercially available visible (650-690nm) vertical-cavity surface-emitting laser.

FSO-based communications equipment from companies such as Lightpointe, MRV and Terabeam target those areas where the quick set-up of links is needed (e.g. in Eastern Europe, China and Africa, as well for military applications). With VCSELs in the power range of 12–60 mW (such as those from U-L-M Photonics), edge-emitting lasers are systematically being replaced in FSO equipment. Such optical wireless transmission reduces deployment times for networks and offers high bandwidth at a comparatively low cost. Transmission speeds of 1 Gb/s are developing, which is fast enough to support video applications over ranges of as much as half a mile.

Tunable VCSELs have the potential for future optical networks. To date, the most successful mechanism for wavelength tunability in tunable VCSELs lies with VCSELs based on microelectromechanical systems (MEMS). To achieve wavelength tuning, controllably movable top mirrors are used. However, this technology is still some way from practical realisation.

Computer mice and displays

One spectacular success outside the telecoms arena has been in cordless mice. Logitech's laser mouse is still a very popular ergonomic solution. Also, Avago Technologies (formerly Agilent Technologies) recently shipped its 500 millionth mouse sensor.

"Logitech's MX1000 cordless laser mouse uses a VCSEL for surface illumination", says Mark Alden of Avago's semiconductor products group. "We worked exclusively with Logitech to develop this revolutionary laser navigation sensor technology, and Avago plans to make it available to other mouse manufacturers."

One thing is for certain: VCSELs will never be all things to all people. For example, thanks to the small size of the cavity, VCSELs are intrinsically lower-output power devices, and thus VCSELs

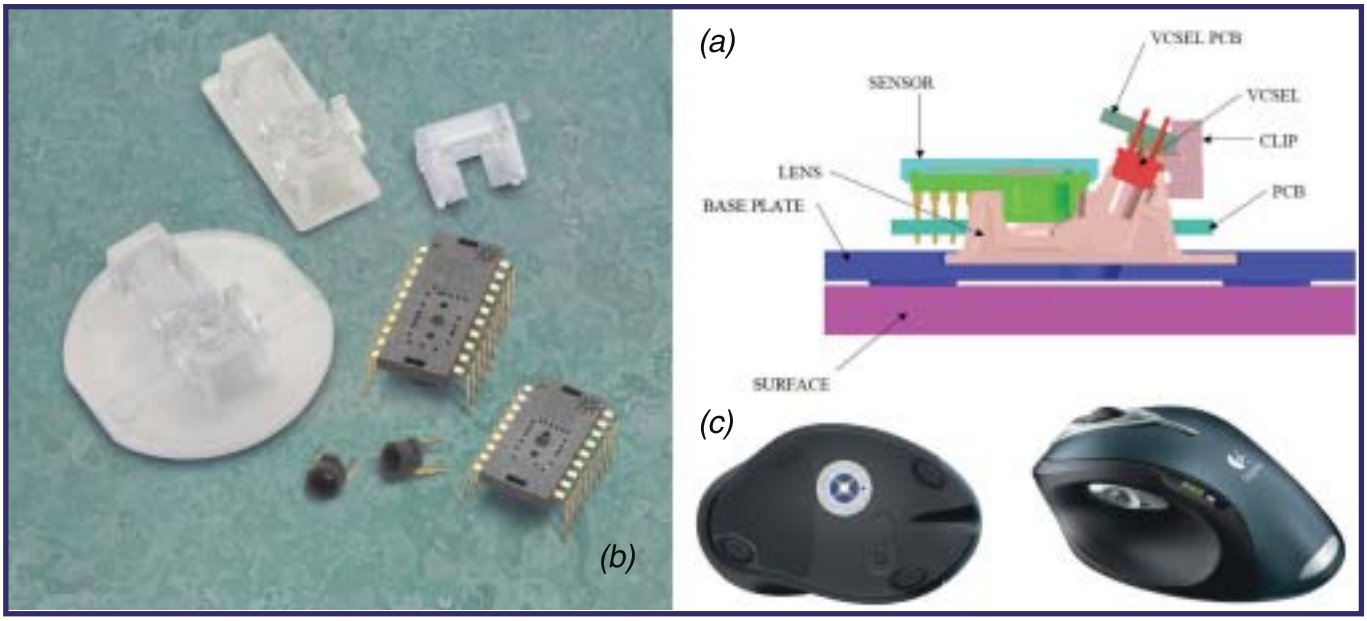

Figure 2. Laser mice built around Avago's LaserStream technology provide positioning accuracy with resolution up to 2000 counts per inch, and can keep up with rapid movements with maximum velocities of up to 45 inches per second and accelerations of up to 20g. (a) Cross section of mouse components assembly. (b) The LaserStream navigation sensor bundle (shown are two mouse sensor bundles that include the sensor, VCSEL, round or rectangular lens, and a VCSEL assembly clip). (c) The underside of Logitech's MX1000 cordless laser mouse (powered by LaserStream).

will most likely not be able to compete in higher-power applications such as fibre pumping or data storage etc. With data storage now the biggest single application for lasers, this is bad news for VCSEL suppliers. The VCSEL can really compete best in the applications where the required power level is low.

However, another major market could become an end-user for VCSELs — as light sources in rear-projection television (RPTV). A VCSEL system developed at Principia Lightworks, called the eVCSEL, is a low-cost laser intended for use in RPTVs. Red-green-blue eVCSELs are placed in a CRT then scanned by the laser beam. The eVCSEL does not require optical transparency for either the bonding layer or the substrate, and cooling is achieved by forced-air convection, which yields a useful lifetime that is better than conventional lamps.

Industrial and elsewhere

Despite being dominated by fibre networks, U-L-M Photonics' Dr Burghard Schneider explains that there are markets for VCSELs that target the real advantages: "On the other hand, VCSELs are the ideal light source for spectroscopy, being both transversal and longitudinal single-mode. These single-mode applications allow quantitative detection of, for example, oxygen (759 nm) and moisture (795 nm). Analytical instrumentation is a small but growing market. Plus, VCSELs are used as low-cost 852 nm single-mode sources for activating Cs and Rb in atomic clocks, which look promising for global positioning systems (GPS)."

Firecomms, as well as other manufacturers, have developed 650–680 nm VCSELs that have much promise for new applications, such as medical and data reading/capture as well as for fibre-optic communications. High-power VCSELs are also used for range finders, for homing devices, and for lighting.

There is also much potential in the automotive industry, such as for 'Fibre-in-the-Car'. This area has seen some major changes, with more to come thanks to the arrival of 'MOST'. This acronym stands for media-oriented systems transport. MOST is a collaborative specification that brings together auto companies and makers of in-car systems such as radios etc. MOST is a fibre-optic automotive network for real-time data transfer that allows components from different brand aftermarket suppliers to interact with each other. Gary Shapiro, president and CEO of the US-based Consumer Electronics Association, has said that: "We believe that working with the MOST can help alleviate challenges to connectivity and support the rising sales of mobile video, navigation devices and aftermarket audio equipment and provide consumers with more choices in determining their in-vehicle products." It is clear that VCSELs could potentially be the enabling technology for this very important new development.

Next-generation high-density form factors will strongly favour exclusive use of VCSEL technology due to its low heat and low EMI-generation characteristics

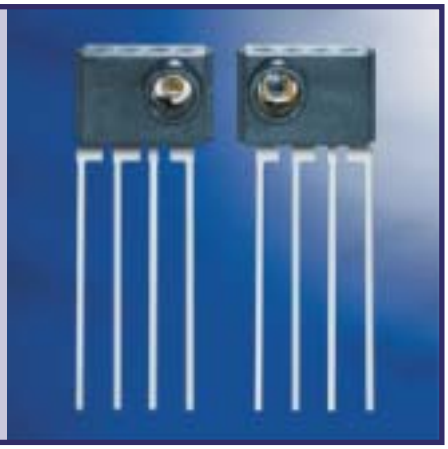

Figure 3. U-L-M Photonics has developed and qualified VCSELs that show very good stability over temperature, which is the main challenge besides reliability. (Photo courtesy of U-L-M Photonics.)

It may have been underestimated by some start-ups what was needed to get VCSELs into genuine production. The VCSEL array market proved disappointing but has seen some recovery

Also, VCSELs with high power — up to 1W pulsed — could be used as a substitute for onboard radar or night-vision systems in a cheap, robust, low-cost light source as a VCSEL array. However, Firecomms in 2005 revealed how its resonant-cavity LED (RCLED), rather than its VCSEL-based POF technology, was at the heart of a Renault concept vehicle. The reason for this is that the RCLED is deemed to meet the tough temperature requirements for automotive electronics.

Today, companies such as DaimlerChrysler and BMW are looking into POF with LEDs, but in due course POF and 850 nm VCSELs will come offering better power budget and higher bandwidth compared to LED solutions. In this regard, U-L-M Photonics* has developed and qualified VCSELs that show very good stability over temperature which is the main challenge besides reliability (vehicle applications have to be qualified over the range –40°C to +125°C) — see Figure 3.

There is also the home and office printer market for monolithic VCSEL arrays — either multimode or single-mode, depending on the technology used — and Xerox has already developed a VCSEL-based printer.

Furthermore, long-wavelength VCSELs could help to overcome eye-safety problems in applications like parallel optical data links. These will provide the cost and performance benefits of today's short-wavelength VCSELs, but also offer the extra benefits of transmission in the 1300 nm window.

The next steps

Further in the future, VCSELs could help to implement next-generation computing and communications systems via board-to-board and chip-to-chip photonic interconnects. Since all-optical systems are not yet practical, this is still a market with potential. VCSELs have the advantage of being able to be set up as monolithic arrays. Large numbers of channels allow optical computing using 256 channels. Intel has made a commitment to such technology, where it could use 1310 nm VCSEL emitters working with silicon, because silicon is transparent at the 1310 nm wavelength.

The 3-D OESP consortium (Honeywell Technology Center and University of California, Santa Barbara) has demonstrated FSO links operating between VCSEL arrays and detector arrays at up to 2.5 Gb/s. High-performance workstation manufacturers are struggling to resolve communication bottlenecks at the board-to-board level. Hence, board-to-board interconnect solutions using FSO are now being evaluated by the computer industry, and chip-to-chip interconnects are being investigated at the fundamental level at several universities, including University of California, San Diego. In particular, the latter has developed and demonstrated a fully packaged FSO system for multi-chip interconnections that is capable of sustaining channel data rates as high as 800 Mb/s.

* See www.ulm-photonics.de/docs/pr/PW05_Auto.pdf

	2003	2004	2005	2006	2007	2008
Automotive	18	23	27	30	33	38
Computer	65	79	94	105	114	133
Consumer	63	77	93	103	112	131
Industrial	30	37	44	49	53	62
Military/Aerospace	20	24	29	32	35	41
Telecoms	25	31	37	41	45	52
Other	9	11	13	15	16	19
Total	**231**	**282**	**337**	**375**	**407**	**477**

Table 1. Global VCSEL market in 2003-2008 by application (US$ million). Long term, the market will see growth through factors such as the rise in high-capacity optical networks, interest in shifting wavelength to increase data capacity, and applications such as sensors. (Source: 3rd edition of "Optoelectronics A Strategic Study of the Worldwide Semiconductor Optoelectronic Components Industry to 2008", Reed Electronics Research, www.rer.co.uk/publications/active/optoelectronics.shtml).